

CFD based Prediction of Spin Power Loss of Automotive Differential System

S Renjith, Vinod Kumar Srinivasa, and Biswadip Shome
Tata Technologies Ltd

ABSTRACT

In an automotive power train system, the differential gear system plays a vital role of enabling the vehicle to transfer the engine torque to the wheels. The differential system consists of complex system of gears which are meshed with each other. Effective lubrication of the differential system ensures that the metal to metal contact between the gears is avoided. In addition, the lubricants also acts as a thermal medium to effectively dissipate the heat produced due to frictional resistances. For dipped lubrication system, the use of lubrication oil leads to a loss of transmission power, and the loss increases with increasing rotational speeds.

Prediction and an understanding of the transmission loss inside the differential system is important as it provides a means to increase the power transmission efficiency. In addition, it provides insights to optimize the lubrication methods, gear profile, and gear housings.

In this study, the load-independent power losses of an automotive differential system operating under dip-lubrication conditions is investigated using Multiphase Computational Fluid Dynamics analysis with the Volume of Fluid approach. The investigation is conducted for a differential system filled with lubrication oil up to the center level of the ring gear and for the case with gear blanks without teeth to compare the results and formulate the spin power losses.

The results from this investigations show total power consumption by the differential system and the lubrication flow characteristics. Power estimated in dip oil lubrication case is compared with no oil case to assess the additional power requisite due to drag offered by oil. Difference in total power consumption for the differential system with family of blank gears as compared to later case is caused by the spin power loss due to the actual differential system. Since both air and lubrication oil interaction with gears captured during the unsteady state CFD simulation, the power loss due to air windage, and oil churning losses are accounted. Estimating the power losses generated by a differential system in advance during the design step allows saving time and money normally needed in order to realize prototype and to test them. Furthermore, the information about the internal fluid dynamics of the differential system should help the designers in the optimization of not only the lubrication but also the heat dissipation.

CITATION: Renjith, S., Srinivasa, V., and Shome, B., "CFD based Prediction of Spin Power Loss of Automotive Differential System," *SAE Int. J. Commer. Veh.* 8(2):2015, doi:10.4271/2015-01-2783.

INTRODUCTION

A differential system, shown in [Figure 1](#) consists of one input, the drive shaft, and two outputs which are the two drive wheels, however the rotation of the drive wheels are coupled by their connection to the roadway. Under normal conditions, with small tire slip, the ratio of the speeds of the two driving wheels are defined by the ratio of the radii of the paths around which the two wheels are rolling, which in turn is determined by the track-width of the vehicle (the distance between the driving wheels) and the radius of the turn.

The differential system allows the automobiles and wheeled vehicles to take turns at corners by rotating outer wheels faster than the inner drive wheel. This is necessary when the vehicle turns, making the wheel that is traveling outside of the turning curve roll farther and faster than the other. The average of the rotational speed of the two driving wheels equals the input rotational speed of the drive shaft. An

increase in the speed of one wheel is balanced by a decrease in the speed of the other wheel and this has significant influence on the drag force that the gear assembly experiences.

The norms and regulations for carbon emissions and efficiency requirements on passenger vehicles and heavy trucks are becoming increasingly stringent globally. Increasing fuel costs is a major driver for improving the fuel efficiency. These highly contending requirements necessitates a great scrutiny of each and every single component design for its power transmission efficiency. Since there is not a single power loss source that dominates the overall transmission efficiency, every source must be examined and minimized if possible, regardless how low they are, such that desired increase in efficiency can be achieved.

Increasing the fuel economy is not the only benefit of increasing the power transmission efficiency or reducing the transmission losses. Gear and bearing contacts leads to high temperatures. Lower power

losses equate to less heat generation in the differential casing, which improves the contact fatigue and scuffing performance of the gears and bearings. Furthermore, the capacity and extent of any lubrication system is also determined by the amount of heat that must be removed from these critical contact zones. As such, design and durability of transmission systems are also influenced by their efficiency.

Reducing the power transmission losses of the automotive differential system entails a careful inspection of all sources of power losses within the system. Focusing on the geared components of the transmission, the primary sources of power loss can be broken down into two categories [2], load-dependent (mechanical) power losses and load-independent (spin) power losses as shown in Figure 2. Mechanical power losses in gears primarily consist of frictional gear tooth interactions at the gear mesh, where the two primary modes of power loss are the rolling friction associated with the formation of an Elasto Hydrodynamic Lubrication (EHL) film between meshing teeth and sliding friction associated with combined sliding-rolling velocities, normal forces, contact curvatures, and surface roughness. Alternatively, spin power losses in gears are associated with the interactions of the gear bodies with fluid medium around them. Two main components of gear spin power losses are: (1) Drag losses associated with churning of the oil or windage of air (or an oil-air mixture) along the side faces and periphery of gears, and (2) Pocketing losses associated with pumping of fluid medium from pockets formed between adjacent teeth at the gear mesh interface. Each component of power loss is associated with certain operating conditions. Mechanical losses are most significant at high-load, low-speed conditions when the fluid film formed at the contact interfaces is the least favorable, causing significant friction.

Numerous investigations have been done both experimentally [3, 4, 5], and numerically [6, 7, 8, 9]. Some of the investigations are being done on the windage power losses and influence of the helix angle [7] using CFD. Dawson [3] ran experiments using toothed wheels and Discs which showed that gear teeth have a significant impact on windage losses, i.e. modeling gears as solid cylindrical disc might cause significant errors. It was also found that a larger helix angle of the gear tooth lowered windage power loss. Lord [12] expanded on Dawson's experiments by adding several helical gear measurements. A CFD based simulation approach used in this paper has been used for a gear box problem and the results are verified by use of the physical test result by Carlo Gorla [13].

Automotive transmissions mostly incorporate dip-lubrication techniques where the gears are partially immersed in lubricant and the motion of the gears supplies the circulation necessary to lubricate gear meshes and bearings. The studies that focus on load-independent losses can be classified into those that investigate windage power losses and those investigating churning power losses. Windage and churning are not mutually exclusive, but are often studied separately by making assumptions based on operating conditions. The energy

required by the system to rotate the partially immersed gears and bearings is referred to as churning loss and losses due to the sweeping of the air known as windage losses are the primary focus of this study. Many studies have been conducted in this account by considering gears alone but this paper investigates the entire differential system in the context of spin power losses.

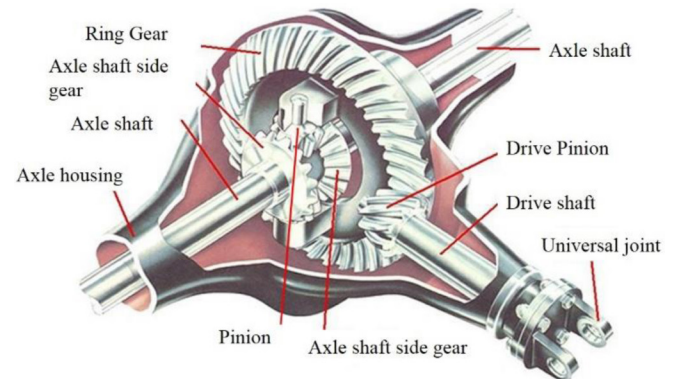


Figure 2. Components of power losses in a geared system [2]

In this study a high quality computational model is developed to investigate spin power losses of an actual differential transmission system within wide ranges of speed and mesh configuration. It is anticipated that the database formed in this study will be instrumental in future modeling efforts in terms of the selection of assumptions employed, as well as validation of predictions. The automotive differential system considered in this study, as shown in Figure 3, consists of the ring gear, side gears, pinion gears, driving gear, differential casing, and housing. Major dimensional parameters for driving and ring gear are summarized in Table 1.

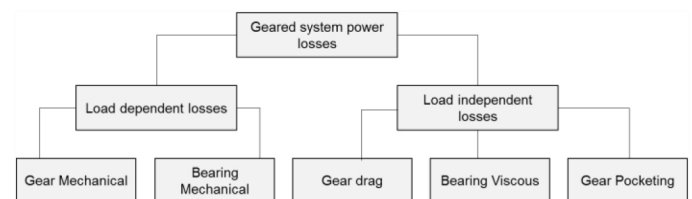


Figure 1. Components of an automotive differential system [1]

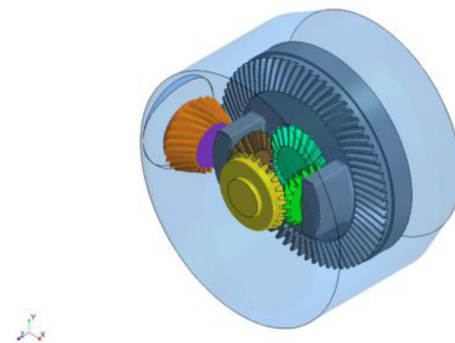


Figure 3. Components of an automotive differential system considered for spin power loss assessment

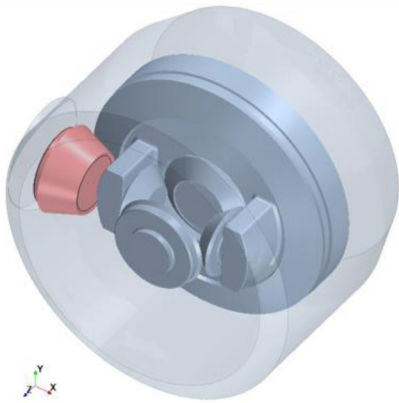


Figure 4. Automotive differential system with idealized gears as discs to compute the spin power loss

Table 1. Gear dimensions

Parameters	Pinion Gear	Ring Gear
Outer Radius	24.9 mm	69.6 mm
Inner Radius	18.1 mm	50.5 mm
Mean cone radius	21.5 mm	60.1 mm
Number of teeth	23	69
Mean Spiral angle	22.2 °	22.2 °

Usually the gear meshing will result in contact of the surfaces however in this study gears are placed in such a way that there exist a fine gap between the gears to ensure smooth and gradual progressing of mesh with the predefined quality criteria for numerical iterations and CFD requirements. Total torque on both driving gear and ring gear are considered here as output parameters. Straight line motion of the vehicle is considered here resulting in the motion of two components such as driving pinion and ring gear and associated components as whole. Power consumptions of gears such as driving gear, ring gear, and associated gears are computed and reported in this study

NUMERICAL METHOD

In this study, an unsteady incompressible three-dimensional CFD analysis is used to simulate the lubrication oil dynamics inside the differential system using the commercial STAR-CCM+ software [15]. The turbulence was modeled using the Realizable k- ϵ model with Two layer all y+ wall treatment [17].

The gear rotations are modeled using the mesh overset method [15, 16, 17] in Star CCM+ which is a more time efficient technique than conventional dynamic mesh options. Overset meshes, also known as “Chimera” or overlapping meshes, are used to discretize a computational domain with several different meshes that overlap each other in an arbitrary manner. They are most useful in problems dealing with multiple or moving bodies, as well as optimization studies. In

most cases, using overset meshes does not require any mesh modification after generating the initial mesh, thus this technique offers a greater flexibility over the standard meshing techniques which result in considerable savings in computational efforts.

Lubrication oil dynamics and oil surface interaction with the air is modeled using VOF multiphase approach [15, 16, 17] in Star CCM+. VOF is a simple multiphase model best suited for flows with several immiscible fluids on numerical grids as this is capable of resolving the interface between the phases of the mixture. Due to its numerical efficiency, the model is suited for simulations of flows where each phase constitutes a large structure, with a relatively small total contact area between phases. If the fluid body movement becomes pronounced, it results in breaking waves, large numbers of oil droplets in the air. The method required a fine mesh, at least three cells across each droplet/bubble as thumb rule to reduce small modeling errors.

COMPUTATIONAL DOMAIN AND BOUNDARY CONDITIONS

The CFD simulation used in this study employed a computational domain as shown in Figure 5. The computational domain used in this study captured all the actual components inside the differential system with adequate geometric accuracy. In an overset mesh, cells are grouped into active, inactive, or acceptor cells. Within active cells, discretized governing equations are solved. The solution is computed for all active cells in all regions simultaneously, that is, the meshes are implicitly coupled. When a reference is made to the variable value in an acceptor cell of one mesh within the discretized equations, a blend of variable values at donor cells from the other mesh is used. This value is reflected directly in the coefficient matrix of the algebraic equation system. This tight coupling of the overset and background regions allows for a solution that is within an arbitrary low level of iteration errors.

Multilevel volumetric refinement strategy is used to meet the overset mesh criteria and to ensure the proper solution convergence. Trimmer mesh with prismatic boundary layer mesh continua has been used for domain discretization as shown in Figure 6. Gear surfaces are meshed with an average mesh size of 0.20 mm. To capture boundary layer effect and to capture viscous drag forces on the wall more precisely which is, two layers of prismatic prism layer of absolute cell size of 0.01 mm has used. Maximum cell size in the domain has restricted to 2.00 mm and the vicinity of overset boundary interfaces are restricted to 0.3 mm by multiple volumetric refinement as visible in Figure 5 and Figure 6. Volumetric refinement and tightly controlled mesh development resulted in total cell count of around 20 million. To understand the sensitivity of the result to the mesh size, a mesh independent study is done by refining the volume mesh further to around 40 million and 60 million cells. The difference in the predicted power loss was less than 7.8%. Based on this result, the